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(54) **Seismic noise filtering method**

(57) A method for filtering noise from discrete noisy seismic signals in a time interval ([1, ..., T]) is provided said method comprising the steps of
- using said noisy seismic signals for determining at least one reference channel (x(t)) for said time interval as an estimate of said noise;
- determining coefficients for M temporally local filters (w(i,t)), said filters forming a filter bank, and M being a number equal to or larger than two, by minimizing a cost function (J(t)) representing a measure of the error of the output of said filter bank; and
- applying said filter bank to said at least one estimate (x(t)) to determine M filtered estimates of said noise. The filtered estimates are multiplied with temporal windows (h(i,t)).

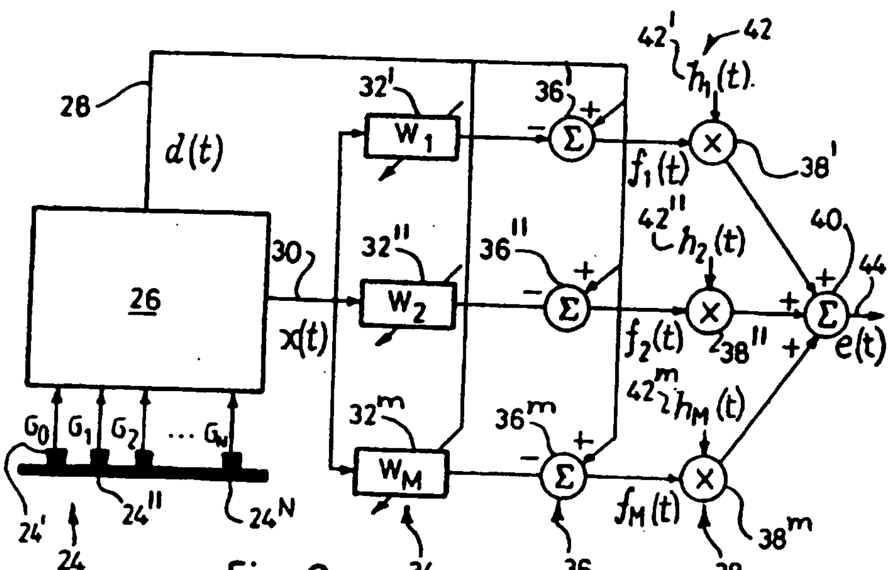

Fig. 2

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

This print incorporates corrections made under Section 117(1) of the Patents Act 1977.

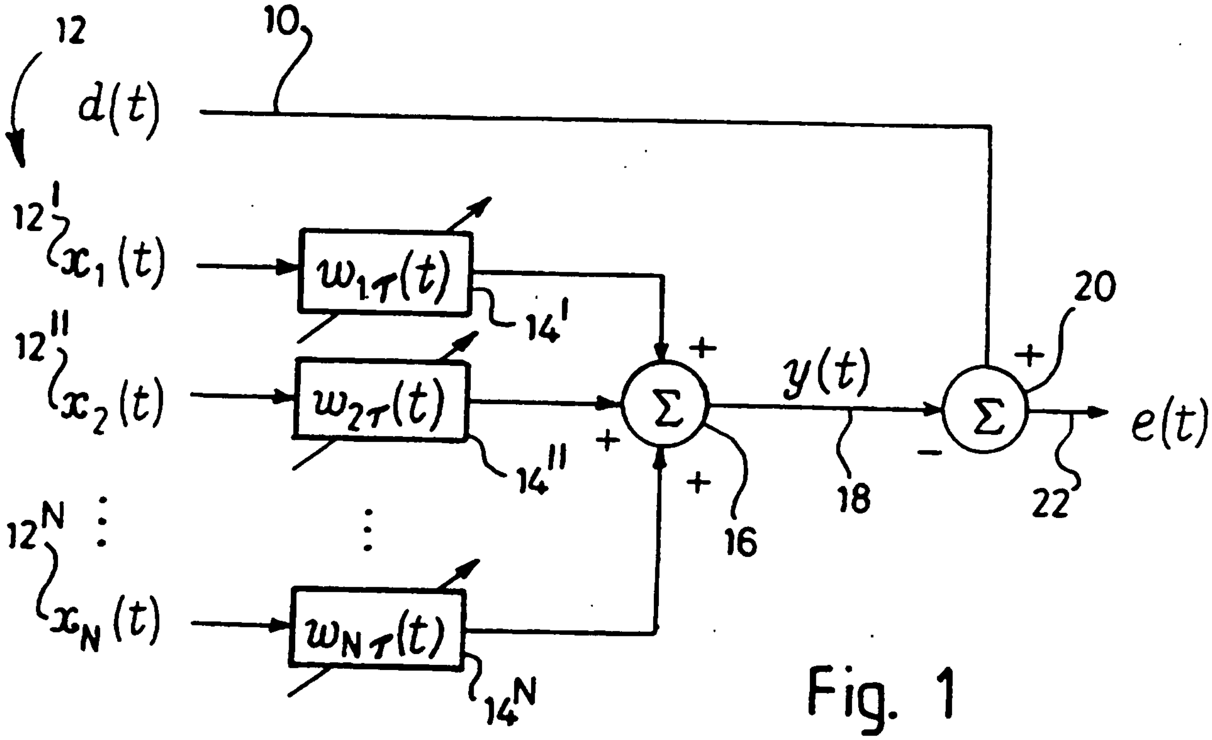

12
10
d(t)
12'
$x_1(t)$
$w_{1\tau}(t)$
14'
12''
$x_2(t)$
$w_{2\tau}(t)$
14''
12^N
$x_N(t)$
$w_{N\tau}(t)$
14^N
+
+
+
Σ
16
y(t)
18
+
−
Σ
20
e(t)
22

Fig. 1

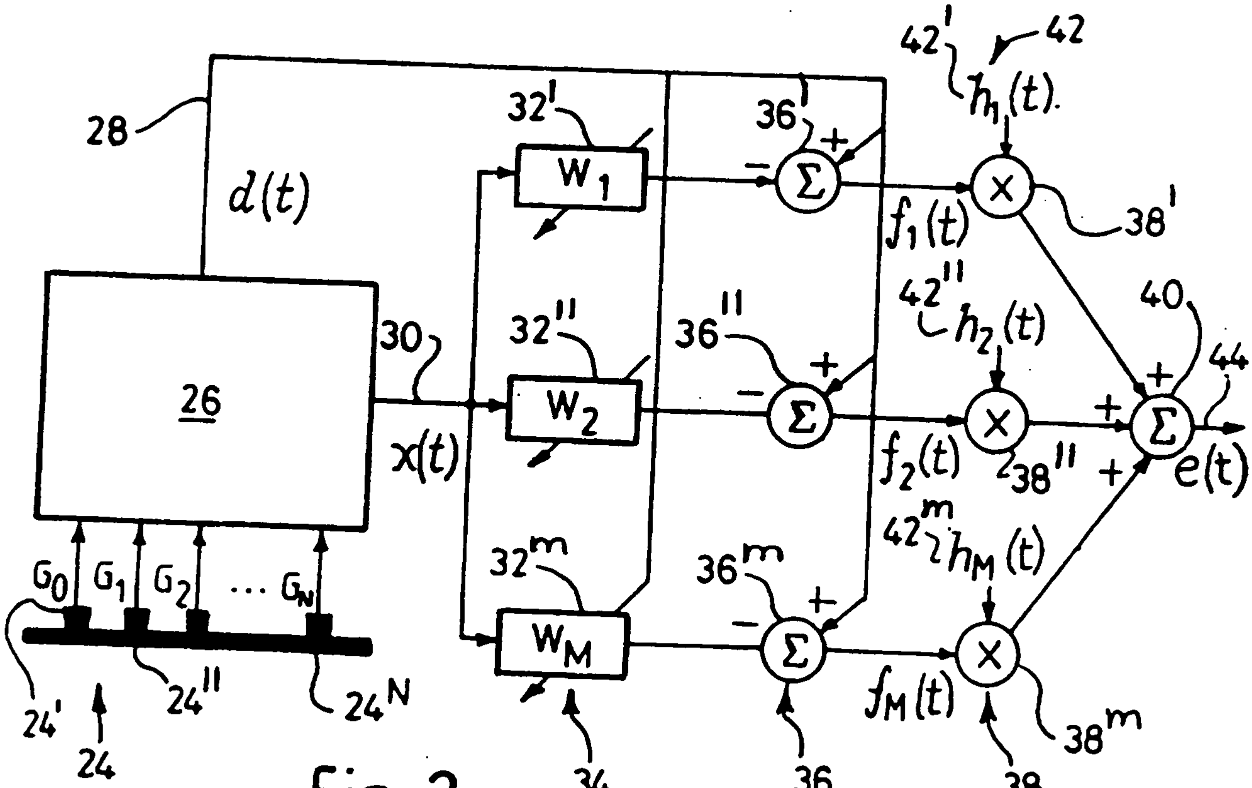

28
d(t)
26
30
x(t)
G_0 G_1 G_2 … G_N
24'
24''
24^N
24
32'
W_1
32''
W_2
32^m
W_M
34
36'
36''
36^m
36
$f_1(t)$
$f_2(t)$
$f_M(t)$
42'
42
$h_1(t)$
42''
$h_2(t)$
42^m
$h_M(t)$
38'
38''
38^m
38
40
44
e(t)

Fig. 2

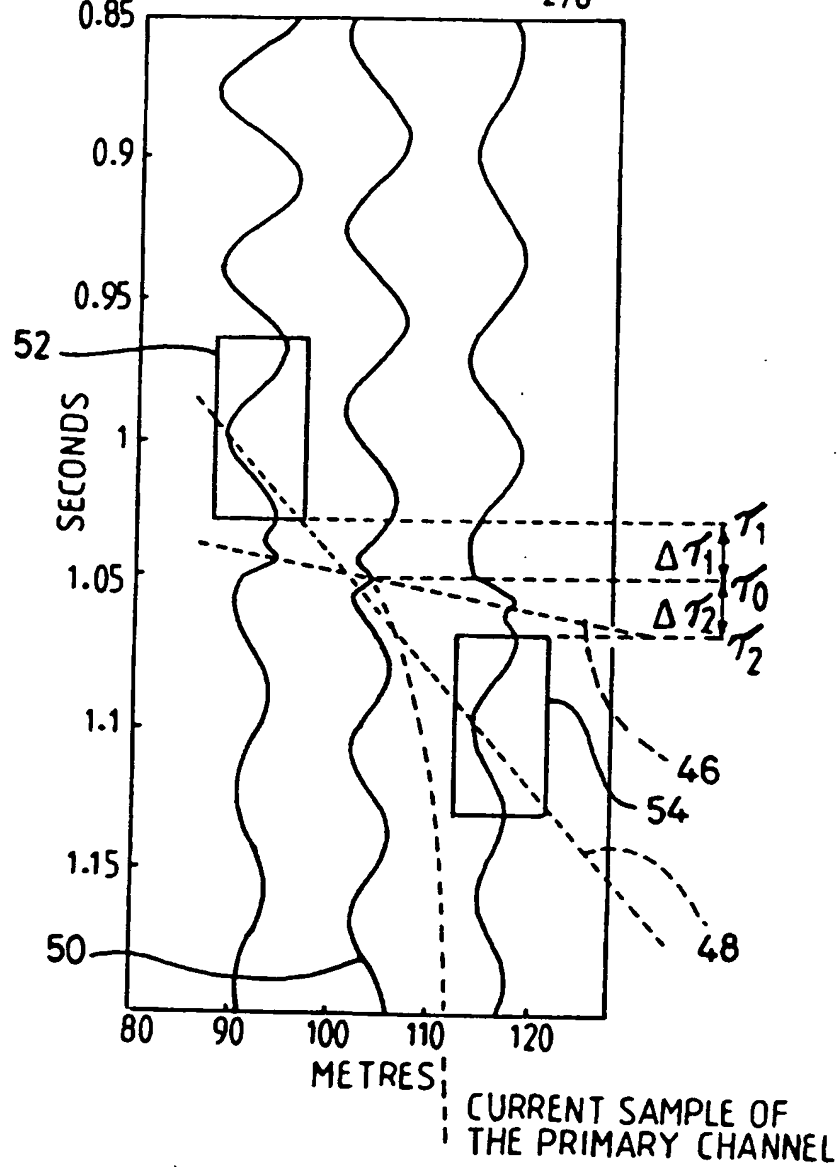

0.85
0.9
0.95
1
1.05
1.1
1.15
SECONDS
52
50
τ_1
$\Delta\tau_1$
τ_0
$\Delta\tau_2$
τ_2
46
54
48
80
90
100
110
120
METRES
CURRENT SAMPLE OF
THE PRIMARY CHANNEL

Fig. 3

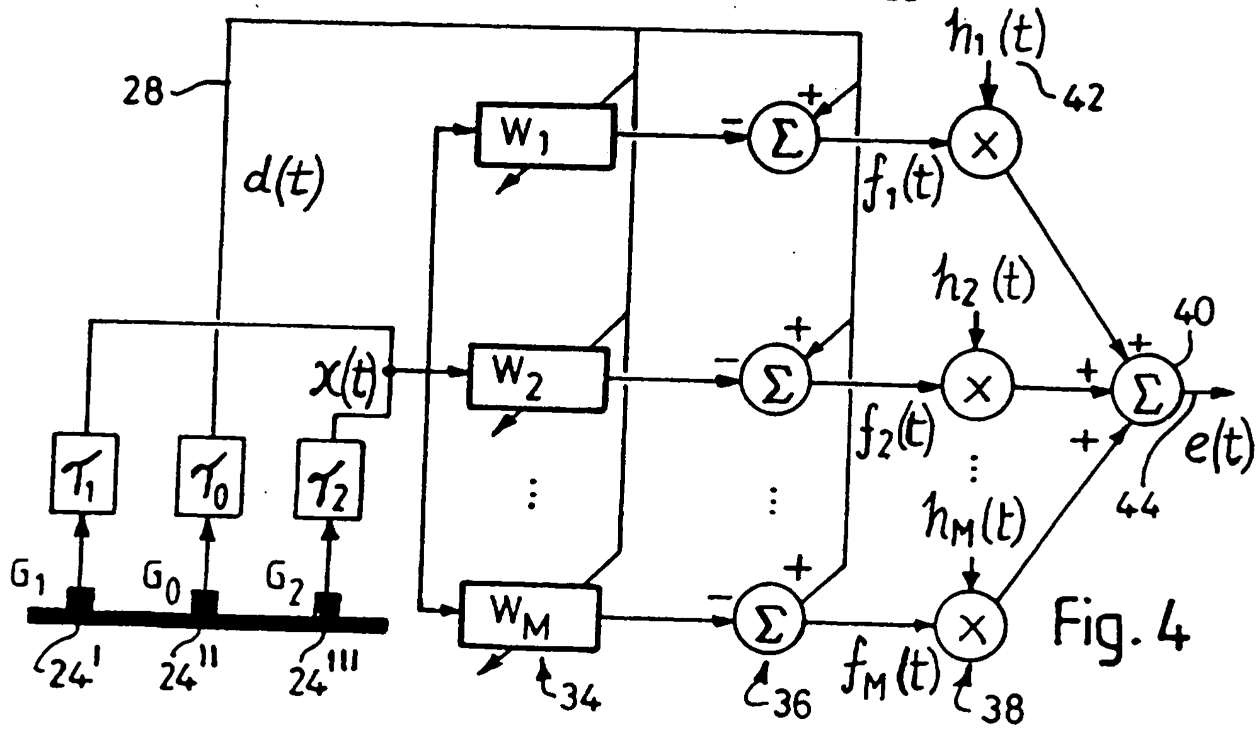

28
d(t)
x(t)
τ_1
τ_0
τ_2
G_1
G_0
G_2
24'
24''
24'''
W_1
W_2
W_M
34
36
38
$h_1(t)$
$h_2(t)$
$h_M(t)$
42
$f_1(t)$
$f_2(t)$
$f_M(t)$
40
44
e(t)

Fig. 4

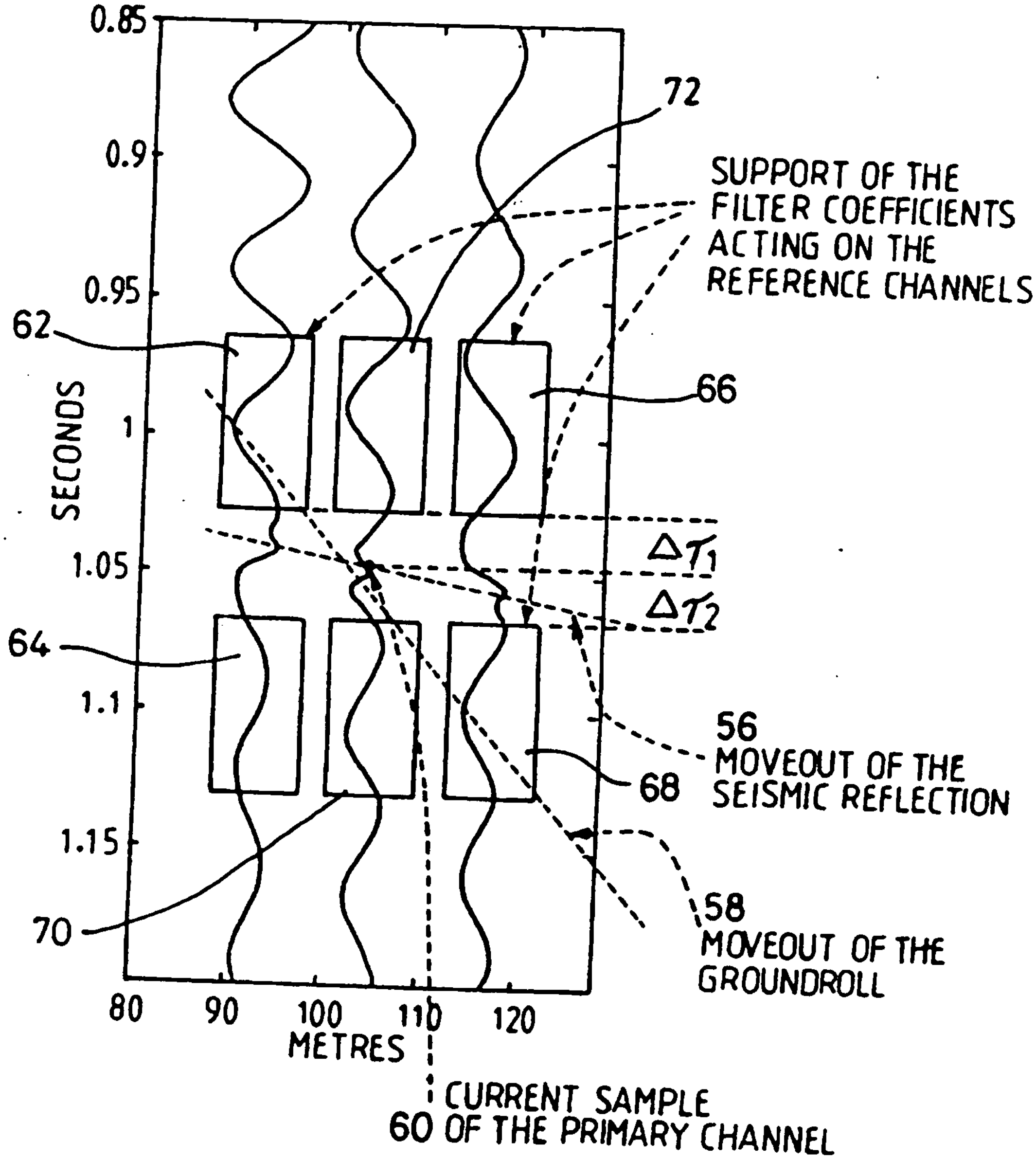
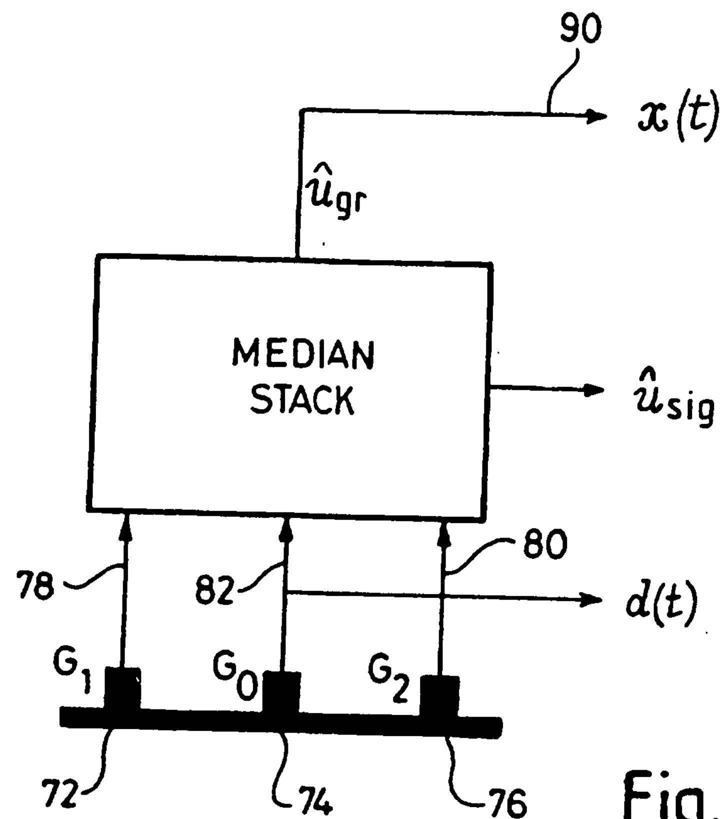
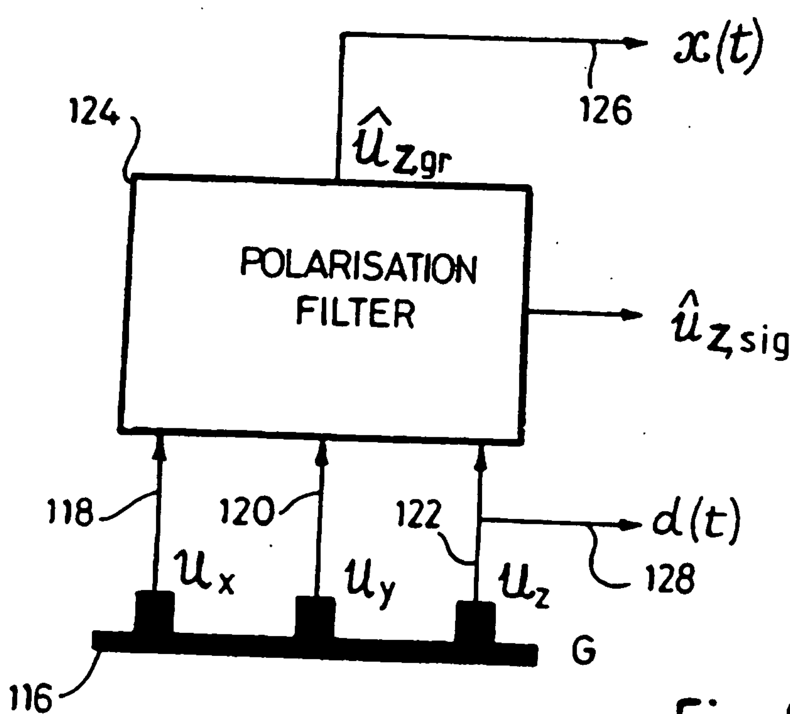

0.85
0.9
0.95
1
1.05
1.1
1.15
SECONDS
80
90
100
110
120
METRES
62
64
66
68
70
72
SUPPORT OF THE FILTER COEFFICIENTS ACTING ON THE REFERENCE CHANNELS
$\Delta\tau_1$
$\Delta\tau_2$
56 MOVEOUT OF THE SEISMIC REFLECTION
58 MOVEOUT OF THE GROUNDROLL
CURRENT SAMPLE 60 OF THE PRIMARY CHANNEL

Fig. 5



90
x(t)
û_gr
MEDIAN
STACK
û_sig
78
82
80
d(t)
G1
G0
G2
72
74
76

Fig. 6



x(t)
124
126
û_z,gr
POLARISATION
FILTER
û_z,sig
118
120
122
d(t)
128
u_x
u_y
u_z
G
116

Fig. 8

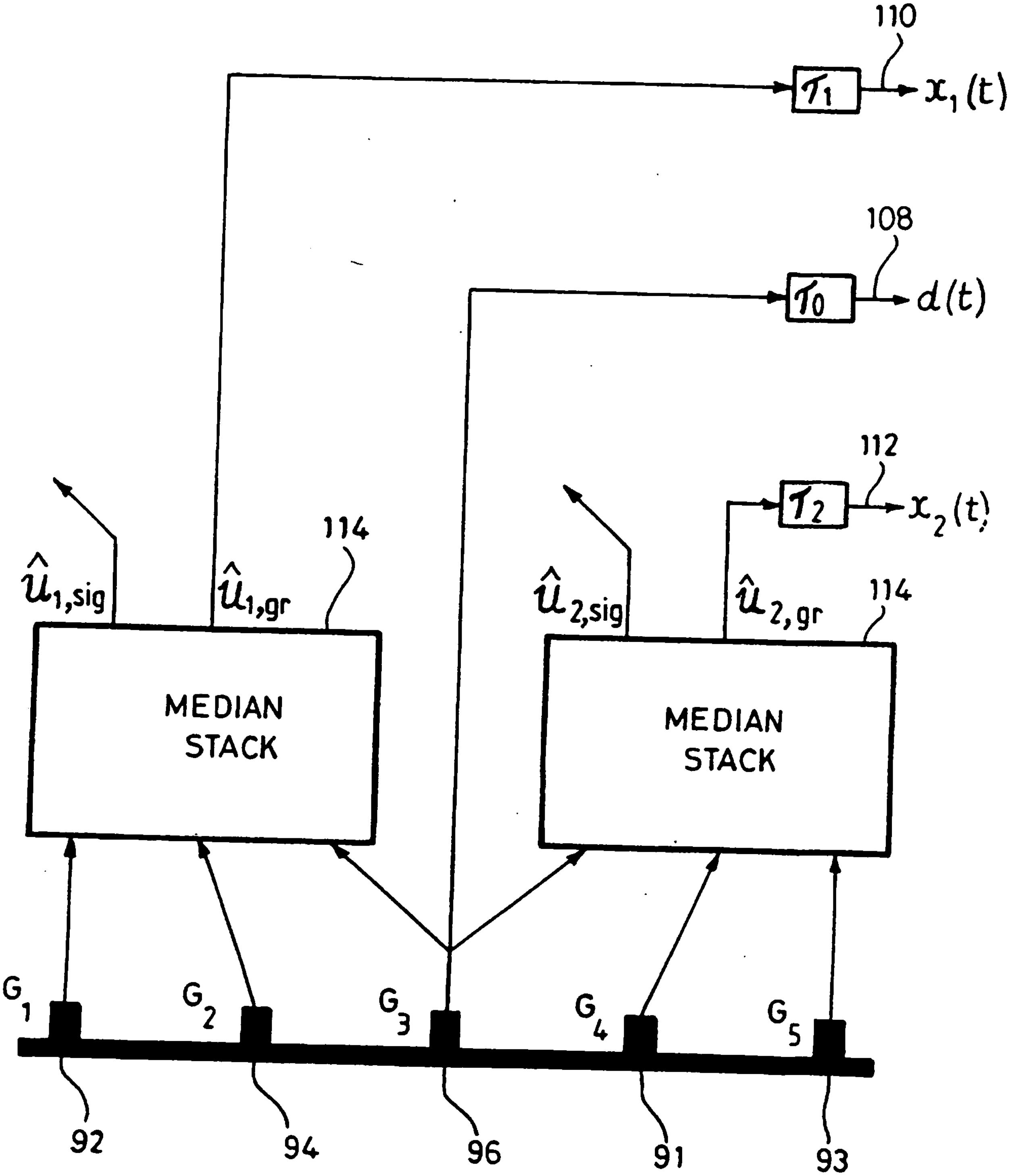

110
τ_1
$x_1(t)$
108
τ_0
$d(t)$
112
τ_2
$x_2(t)$
$\hat{u}_{1,sig}$
$\hat{u}_{1,gr}$
114
$\hat{u}_{2,sig}$
$\hat{u}_{2,gr}$
114
MEDIAN STACK
MEDIAN STACK
G_1
G_2
G_3
G_4
G_5
92
94
96
91
93

Fig. 7

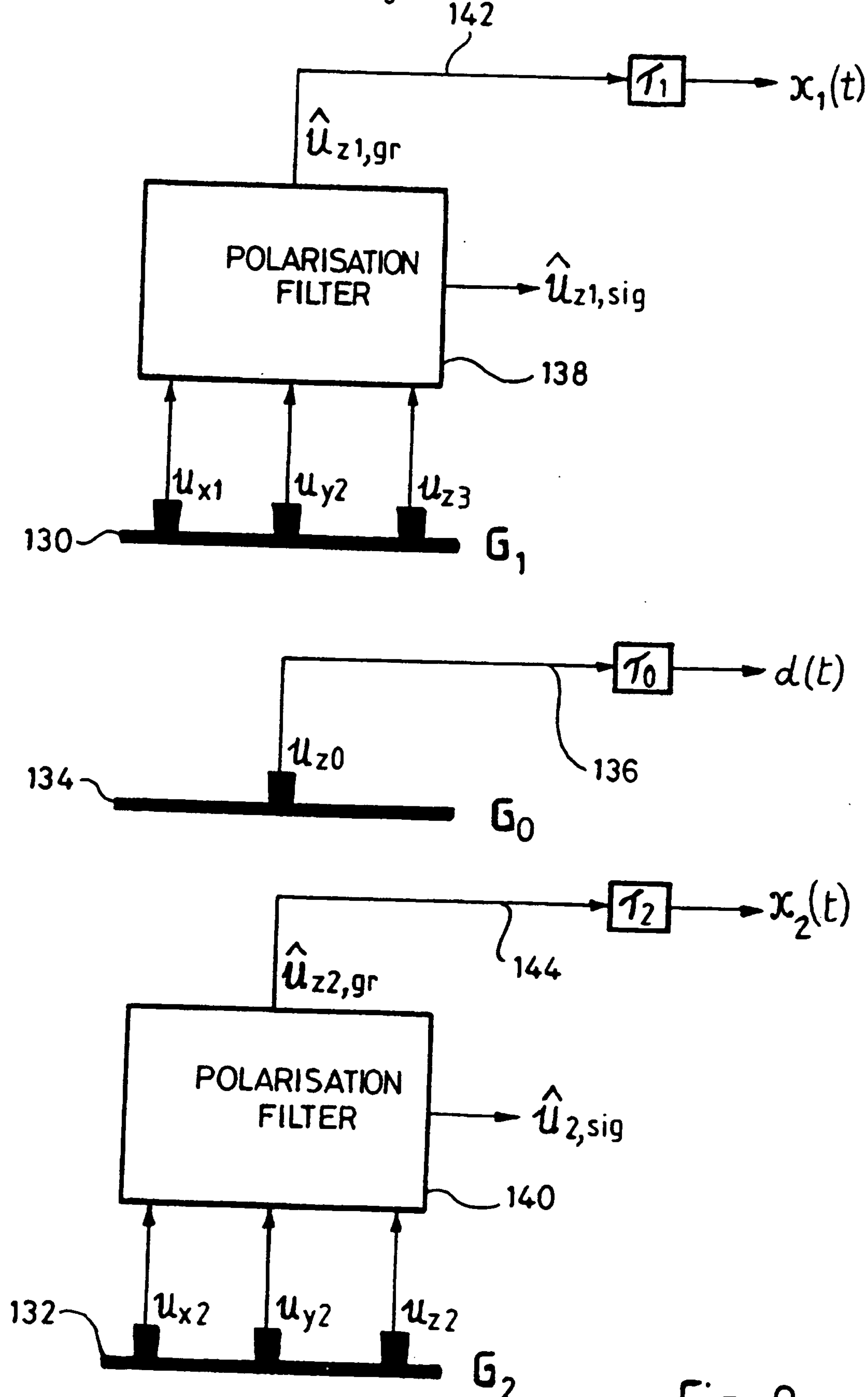

142
τ1
x1(t)
ûz1,gr
POLARISATION FILTER
ûz1,sig
138
ux1
uy2
uz3
130
G1
τ0
d(t)
uz0
136
134
G0
τ2
x2(t)
144
ûz2,gr
POLARISATION FILTER
û2,sig
140
ux2
uy2
uz2
132
G2

Fig. 9

Title: Noise filtering method

Field of Invention

The present invention relates to a method of filtering noise from data signals, and in particular to the filtering of noise so as reduce the effect of coherent noise on data signals acquired during seismic investigations.

Background to the invention

In land seismic surveys, a source induces seismic waves at or near the surface of the earth. These waves propagate through the earth and reflections from different layers within the earth can be detected by sensors, or geophones, at the earth's surface. The seismic source vibrations applied to the earth's surface also generate a so-called surface wave or ground roll which propagates through the shallow layers of the earth. At the geophones, the time of incidence of the low frequency, low speed ground roll typically coincides with the incidence of reflections from the deep layers of interest in the seismic survey. The simultaneous presence of the ground roll with the reflected signals makes it difficult to make full use of the seismic data as the ground roll often masks the reflected waves.

Several methods are known for attenuating ground roll interference and thus reducing its effect on the seismic signal of interest. Typically, geophones are not used individually, but rather are connected in sub-arrays, or groups, which are hard-wired or summed together. This is a form of data-independent beamforming. Attempts have also been made to apply adaptive signal processing for the suppression of ground roll in seismic surveys.

US Patent 4,556,962 attempts to attenuate the ground roll from a surface seismic source by placing a sensor close to the source to detect the interfering noise. The interfering noise is scaled, delayed and summed with signals from a more distant geophone array and then cross-correlated with the original vibrational source. This Patent also suggests that an

adaptive filter be used so as to modify the delayed signal to correspond more closely to that detected by the more distant geophone array. However, the ground roll measured close to the source may be substantially different from that received by the geophone array, and the adaptive filter may not be able to deal with this.

In US Patent 4,890,264 a method for suppressing non-uniformly distributed noise generated by surface wave propagation, wind, and machinery is described. Horizontal geophones for detecting surface waves are used with conventional vertically orientated geophones for detecting seismic energy. The outputs of the surface wave detectors are used in conjunction with an adaptive filter to cancel the effects of the surface wave interference. This method for the suppression of ground roll is inherently a multicomponent method. Some seismic wave energy also gets detected by the horizontally sensitive geophones, and this may cause signal cancellation.

In UK Patent Application GB-A-2273358 the use of linearly constrained adaptive beamforming and adaptive interference cancelling beamforming for ground roll suppression was proposed. This method filters signals measured by an array of geophones and sums them in such a way as to preserve signals incident from a preferred direction while suppressing interference incident from other directions. The filtering is performed using a continuously adaptive method with the moveout differential between the seismic reflections and the ground roll being used to form primary and reference channels. The suggested application is in drilling when using a drill as a seismic source, where the ground roll is effectively stationary due to the slow travel of the drill bit and each source receiver position produces a lot of data. This ensures that the stochastic gradient type of algorithms used in the adaptive filters of this method are able to converge. However, in surface seismic experiments the ground roll present is often non-stationary and inhomogeneous and the stochastic gradient type of algorithms may be too slow to converge within the signal envelope.

US Patent 5,237,538 proposes a method for removing coherent noise from seismic data. This method firstly identifies the moveout characteristics of the noise, defines and extracts a space-time gate containing the noise, and removes the moveout to flatten the noise train.

Amplitudes and time variations are then removed from the gate. The coherent noise is estimated using a beamsteer operator (conventional stacking in this case) and filtered. The filtered noise estimate is subtracted from the data trace containing the signal-plus-noise and inverse amplitude scalars are applied to undo the effect of earlier amplitude equalisation. The signal is then moveout restored into the original seismic record. This method has some particular shortcomings for application for ground roll attenuation. First of all, especially for shorter arrays, the signal always leaks into the ground roll estimate. In fact, there is always a component of the signal present at the reference channel which is colocated in time with the signal in the primary channel. On the other hand, when the arrays are allowed to be longer, the dispersion present in the ground roll make it difficult to achieve effective beamsteering.

Summary of Invention

In accordance with the present invention, a method for filtering noise from discrete noisy seismic signals in a time interval ([1, ..., T]), said method comprising the steps of

- using said noisy seismic signals for determining at least one reference channel (**x(t)**) for said time interval as an estimate of said noise;
- determining coefficients for M temporally local filters (**w(i,t)**), said filters forming a filter bank, and M being a number equal to or larger than two, by minimizing a cost function (**J(t)**) representing a measure of the error of the output of said filter bank; and
-applying said filter bank to said at least one estimate (**x(t)**) to determine M filtered estimates of said noise.

Preferably the cost function (**J(t)**) is temporally global, representing a measure of the error of the total output of said filter bank in the time interval([1, ..., T]).

Further the cost function (**J(t)**) may be minimized using the approximation that the sum, weighted by window functions, of the output of adjacent filters of the M filters (**w(i,t)**) is equal when applied to the same signal in time regions where said window functions overlap.

Preferably the method includes the step of multiplying M filtered estimates with temporal window functions ((**h**(**i**,**t**)).

The temporal window functions may be characterized by the requiement that only adjoining windows overlap.

The application of the temporal window functions, and hence the resulting temporal windows, to the combined components ensures that the filtering means is local in time and allows the method adaptively to remove noise from the seismic data in accordance with a global optimisation criterion, e.g. to solve the optimisation of the filtered signal by minimising the mean square value of the filtered signal over time.

The invention is applicable for two-dimensional (2D) and three-dimensional (3D) seismic surveys, and can be used in land seismic, marine seismic including sea bottom seismic, and transitional zone seismic.

The method can be performed on stored data or on raw seismic data as it is acquired. Thus raw seismic data may be filtered according to the method at the data acquisition site. This ensures that a "cleaned" signal is available from the data acquisition site and may be downloaded directly from the site in this form. This reduces the amount of data that must be sent for analysis off-site and reduces the costs and storage problems associated with accumulating sufficient quantities of noisy data for analysis off-site.

The noise or reference signal may be pre-processed before being passed to the adaptive filtering means by dividing the signal into different frequency bands, for example by using a quadrature mirror filter. This allows a reduction in the number of data points to be processed and also allows a reduction in the number of coefficients in the adaptive filtering means.

The data selection temporal window functions are preferably determined by two requirements, wherein the first requirement is that the sum over all windows at any given time equals unity and the second requirement is that only adjoining windows overlap.

These requirements ensure that the global optimisation of the filtered signal can be solved by use of an approximation in which for the sum over all time and all filters and all neighbouring filters, the error function of a neighbouring filter is replaced with the error function associated with the filter itself.

The application of the data selection temporal windows decouples the equation required to solve the optimisation of the filtered signal. The resulting decoupled equation may for example be solved by the method of principal components or alternatively a damped least squares approach.

Where the decoupled equation is solved using the method of principal components, the number of principal components may be adjusted to vary the degree of filtering and achieve the desired accuracy of filtering. The smaller the signal to noise ratio, the greater the number of principal components that are used to achieve filtering.

Preferably the adaptive filtering is achieved by use of a filtering means, or filtering bank, comprising a plurality of local filters. Each local filter may be multichannel filter. In a further preferred embodiment of the invention, the another signal is used to partially configure the adaptive filtering.

In land based surveys, the seismic data signals for use in methods in accordance with the invention may be acquired from at least two seismic sensing means, typically geophones, the sensing means being arranged in a net, where each sensing means is independent of the other, and each sensing means sends data signals to a processing means on site to be filtered in accordance with the invention. A net is defined as an areal array of sensing means, or geophones, where each sensing means is independent of all other sensing means in the net. This differs from prior art arrangements where each geophone is arranged in an interconnected array and the signals received by the geophones are averaged over the array in an attempt to reduce noise effects such as ground roll prior to data processing off-site.

In a further embodiment of the invention, the filtered output signal may be reprocessed in an iterative manner to a further filter the noise, the filter output signal typically being fed back to at least one of the reference signal and filtering means.

The reference signal may be generated by a number of techniques, of which one example is by moveout differentiation of the data signals.

In another technique the reference signal may be obtained by median stacking. This suppresses seismic signals that do not have the same moveout as the noise to be filtered. Thus the contamination of the reference signal with the seismic signal of interest is reduced.

In a combination of these two techniques, median stacking may be followed by moveout differentiation of the stacked signals.

Where the seismic data is obtained from multicomponent sensing means, the reference signal may be obtained by polarisation filtering of each component sensed by the sensing means. This method may be used to enhance the reference signals from adjacent sensing means which is of particular advantage for three dimensional exploration, i.e. three component, and may also be combined with moveout differentiation.

The invention will now be described by way of example and with reference to the following drawings in which;

Figure 1 shows a processing block diagram of a prior art method for adaptive cancelling using a beamforming method;

Figure 2 shows a method of adaptive interference cancelling in accordance with the invention;

Figure 3 shows sampling of the data signals to support the filter coefficients used in the adaptive interference cancelling;

Figure 4 shows a data-adaptive multichannel filter bank according to the invention applying moveout differentiation to the reference channel;

Figure 5 shows an alternative sampling of the data signals to support the filter coefficients used in the adaptive interference cancelling;

Figure 6 shows generation of the reference channel based on moveout differentiation and median stack in the method according to the invention;

Figure 7 shows generation of the reference channel based on median stack and moveout differentiation;

Figure 8 shows generation of the reference channel based on polarisation differentiation; and

Figure 9 shows generation of the reference channel based on polarisation and moveout differentiation.

Referring now to the drawings, Figure 1 shows a multichannel adaptive interference canceller. The system inputs 10, 12 are derived from two sets of sensors, one input 10 being from a primary sensor and successive inputs 12', 12",..12^N from reference or auxiliary sensors. The input 10 comprises an information bearing signal s(t) corrupted by additive interference $n_o(t)$, where

$$d(t)=s(t)+n_o(t) \qquad [1]$$

The correlation of the signal and the noise is assumed to be negligible.

The reference sensors receive the interference references, $x_i(t)$, where

$$x_i(t)=F[n_1(t),n_2(t)\ldots n_N(t)] \qquad [2]$$

and F[...] is a known function to be specified depending on the particular application. It is assumed that the correlation of $x_i(t)$ and the signal s(t) is negligible, whereas $x_i(t)$ and the interference $n_o(t)$ at the primary sensor have significant, but unknown correlation.

The reference inputs 12', 12",..12^N are processed by an adaptive filter bank comprising local adaptive filters 14',14",..14^N and the processed components combined at a summing means 16 to produce an output signal y(t) 18, where

$$y(t)=\sum_{i=1}^{N}\sum_{\tau=0}^{L-1} w_{i\tau}(t)x_i(t-\tau), \qquad [3]$$

and $w_{ik}(t)$ are the adjustable coefficients of the adaptive filters.

Alteration in the coefficients of the adaptive filters alters the output signal 18. Each adaptive filter may be a multichannel filter.

By expanding equation [3] a tap-input vector x(t) at time t can be defined as

$$\mathbf{x}(t) \stackrel{\Delta}{=} [x_1(t),..,x_1(t-L+1),x_2(t),..,x_2(t-L+1),..,x_N(t),..,x_N(t-L+1)]^T \quad [4]$$

and a tap-weight vector at time t as

$$\mathbf{w}(t) \stackrel{\Delta}{=} [w_{10}(t),...,w_{1L-1}(t),w_{20}(t),...,w_{2L-1}(t),..,w_{N0}(t),..,w_{NL-1}(t)]^T. \quad [5]$$

After the reference inputs 12', 12",..12^N have been adaptively filtered, the output signal y(t) 18 is combined with the primary input 10 at combining means 20 to produce a filtered output signal e(t) 22, where

$$e(t) = d(t) - y(t). \quad [6]$$

e(t) is also known as the error signal and a cost function J is defined which is equal to the sum of $e^2(t)$ over all the sample inputs i.e.

$$J = \sum_{t=1}^{T} e^2(t) \quad [7]$$

where T is the total number of samples. The cost function corresponds to the total error energy and by minimising the cost function, and thus minimising the global criterion, e(t) becomes the least square estimate of s(t), i.e. the pure signal with no noise.

Stochastic gradient type algorithms such as least mean square may be too slow in converging to produce an estimate of the signal without noise when incoherent noise is non-stationery and inhomogeneous, such as those encountered in surface seismics. While

the filters are local in space (i.e. the arrays have finite span), they are not local in time. The optimal filters that are computed are time-invariant and thus limited in performance when dealing with an interference environment that is non-stationary, i.e. where the characteristics change appreciably as a function of time. Ground roll is in general dispersive, and as such often displays non-stationary behaviour. The method of adaptive interference cancelling according to the invention estimates the phase and amplitude perturbation effects alongside the seismic signal propagation effects while the adaptive filter coefficients are computed. This makes the adaptive interference cancelling approach robust to phase and amplitude perturbations present in the data.

Figure 2 shows a system for performing a method of filtering noise from a seismic signal in accordance with the invention. The system comprises a plurality of geophones 24', 24",..24^N, a signal generator 26 for generating an input signal channel 28 and reference signal 30, a number of adaptive filters 32', 32",..32^M arranged as an adaptive filter bank 34, summation means 36',36",..36^M, multiplication means 38', 38",..38^M and combining means 40. The geophones 24 are separate sensors placed on the earth's surface in a net to detect seismic waves produced by reflection at layers within the earth in response to a source wave. The geophones are not linked to each other and act to provide a number of inputs to the primary and reference channel generator 26.

Equivalent systems using hydrophones instead of geophones may be used when conducting marine seismic surveys.

The geophones 24 generate an input signal 28 and a reference signal 30. The reference signal 30 is split and fed into a plurality of adaptive filters 32, the adaptive filter processing coefficients being partially dependent on the input signal 28. Various methods for generating the reference signal 30 are discussed later. The individually adaptively filtered signals produced by the filter bank 34 are then summed with the input signal 28 at the summing means 36. The summed signals pass to multiplication means 38 where windows 42', 42",42^M are applied. The output signals from the multiplication means 38 are then fed to the combining means 40 and combined to produce an output error signal e(t) 44. The input signal 28 partially configures the adaptive filters 32. The windows ensure that the

filters are local in time, i.e. the arrays have a finite time span, and can deal with non-stationary noise. The windows may be triangular with a length of 100 samples.

The windows 42 are constrained by

$$\sum_{i=1}^{M} h_i(t) = 1, \qquad t=1,2,\ldots,T \qquad [8]$$

where T is the total number of samples,

and

$$h_i(t)h_j(t) = 0, \qquad j \neq i-1, i, i+1. \qquad [9]$$

The first constraint ensures that the filter bank 34 is equivalent to the single filter case if all the local filters 32 are identical. The second constraint ensures that the windows have compact support. Use of these two constraints enables the global optimisation of the error signal e(t) to be solved.

The optimisation problem is

$$\min_{w_1,\ldots,w_m} \sum_{t=1}^{T} e^2(t). \qquad [10]$$

The total error energy can be expanded as

$$\sum_t e^2(t) = \sum_t [\sum_i h_i(t) f_i(t)]^2$$

$$= \sum_t [\sum_i h_i^2(t) f_i^2(t) + \sum_i \sum_{j=i-1}^{i+1} h_i(t)\, h_j(t) f_i(t) f_j(t)]. \qquad [11]$$

f_i (t is the error function associated with local filter $\mathbf{w}_i$, where

$$f_i(t) = d(t) - \mathbf{w}_i^T(t)\, \mathbf{x}(t) \qquad [12]$$

It can be seen from equation [11] that the optimisation problem leads to a large number of coupled equations for the filters. The second condition imposed on the windows makes the analysis manageable, allowing the following approximation to be made for the second term in equation [11],

$$\sum_t \sum_i \sum_{j=i-1}^{i+1} h_i(t)\, h_j(t)\, f_i(t)\, f_j(t) \approx \sum_t \sum_i \sum_{j=i-1}^{i+1} h_i(t)\, h_j(t)\, f_i^2(t). \qquad [13]$$

This is a very mild approximation as firstly, the approximated second term in [11] is dominated by the first term and secondly, the approximation is milder than the approximation $w_i \approx w_{i+1}$ or $w_i \approx w_{i-1}$. The approximation of equation [13] requires that neighbouring filters produce similar results when applied to the same input data in time regions where adjacent windows overlap, instead of requiring that neighbouring filters are similar on a point by point basis. Thus, the approximation is similar to requiring that the integral of two functions are close, rather than the functions themselves.

Whilst optimisation leads to a large number of coupled equations for the filters, the approximation of equation [13] decouples the optimisation so that

$$\min_{w_1,\dots,w_m} \sum e^2(t) \Leftrightarrow \min_{w_i} \sum_t h_i(t)\, f_i^2(t), \quad i=1,2,\dots, \qquad [14]$$

The matrix normal equations for the components of the filter bank can be obtained, for example by setting the gradient to zero, or by using the principle of orthogonality, to give:

$$\left[\sum_t h_i(t) x(t) x^T(t)\right] w_i = \sum_t h_i(t) d(t) x(t). \qquad [15]$$

This can be solved by various methods, two of which are the method of principal components and the damped least squares approach.

The use of the principal components approach in combination with time delays (i.e. moveout differentiation) to define the filter supports, allows the filters to focus on wave components which have a certain movement and coherency over an extended region of the

data set (ie the ground roll). The method relies on time averaging operations, thus ensuring that features which have coherency over an extended region of the data set have priority in the computation of the filter coefficients. Furthermore, using only a given number of principal components results in only the most dominant coherent components influencing the computation of the filter coefficients. The number of principal components is an adjustable parameter which allows the user to vary the strength of the filter. The greater the number of principal components used, the heavier the filtering. In general the smaller the signal-to-noise ratio, the heavier the filtering that should be applied.

In the damped least squares approach, ill-conditioning is prevented, and the principal components result is approximated, in the sense that components with small associated singular values are de-emphasised. The contributions of the principal components are only slightly altered. The main advantage of this approach is that it is faster as it involves a symmetric matrix which may be solved using, for example, Cholesky decomposition.

A number of methods for generating the interference reference channel for use in a method according to the invention will now be described by way of example.

Method 1 <u>Multiple reference channels based on moveout differentiation</u>

In a seismic gather, the moveout of the reflected energy in general has a different moveout than the coherent noise, such as the ground roll. This property can be used to apply adaptive interference cancelling to the suppression of ground roll. In Figure 3 an example of traces obtained from seismic survey is shown. The moveout of the seismic reflection 46 and the moveout of the ground roll 48 have different gradients. As can be seen, the ground roll has a much steeper dip than the seismic reflection. On the primary channel 50, i.e. the central trace, the seismic signal is superimposed on a certain phase of the ground roll. On the adjacent traces, the same phase of the ground roll does not overlap with the seismic signal. Thus by appropriate sampling of the adjacent traces, a noise reference can be obtained for use in adaptive interference cancelling. The sampling areas 52, 54 provide support of the filter coefficients acting on the reference channel and are obtained at a defined distance from the current sample of the primary trace 50. The relative supports of

the multichannel filter components can be adjusted by delaying the primary and the reference channel inputs by appropriate amounts. Employing the described method of generating the reference channels, the resulting data-adaptive multichannel filter is shown in Figure 4, where equivalent elements to those already described in relation to Figure 2 are shown with corresponding reference numerals. In Figures 3 and 4,

$$\Delta\tau_1 = \tau_0 - \tau_1 \quad [16]$$

and

$$\Delta\tau_2 = \tau_2 - \tau_0 - L \quad [17]$$

where L is the number of coefficients used in the adaptive filter associated with the second sampling.

For illustration purposes, in the rest of this application, the nearest traces on either side of the trace to be filtered are used as noise reference.

The choice of $\Delta\tau_i$ mainly depends on two factors, namely the autocorrelation function of the signature of the seismic reflection, and the moveout of the ground roll. The autocorrelation function of the signature of the seismic reflection depends on the power spectrum of the seismic reflection. In general, the window in time defined by $\Delta\tau_i$ is chosen to be larger than the lag beyond which the autocorrelation function of the signature of the seismic reflection has negligible values. Secondly the sampling of the nearest traces is chosen so that the dominant moveout of the ground roll bisects the sampling area. This reduces effects due to the dispersive nature of the ground roll and its range of apparent velocities.

Method 2 <u>Multiple reference channels based on moveout and spatiotemporal coherency differentiation</u>

The target signal and the interference may have both different moveout (apparent velocity) and spatiotemporal coherency. This often occurs in surface seismic acquisition. The ground roll not only has a different moveout than the reflection signal, but has significantly more spatiotemporal coherency than the seismic reflections, especially in the temporal

direction. This enables a generalisation to be made for defining the supports of the multichannel filter components outlined in Method 1. Figure 5 shows how the generalisation may be used with traces obtained from a seismic survey. The moveout of the seismic signal 56 and the moveout of the ground roll 58 are again of different gradients. Two regions of filter support are specified for each nearest trace either side of the primary channel 60. As for the sampling carried out in Figure 3, the sampling areas, or filter support, 62, 64, 66, 68 leave a band of time samples around the central sample defined by t_0. This is so as to protect the seismic signal.

The ground roll often has temporal coherence over time scales much greater than the seismic signal, and in such circumstances appropriate portions 70, 72 of the central trace (ie the primary channel) may be used as a reference.

This generalisation can be very useful in many applications. When two reference channels are chosen such that one is causal and the other anti-causal with respect to the incidence direction of the direct ground roll as described in Method 1, the output will contain the reflecting event, as well as a precursor (a leading event) which is approximately half the lowpass version of the event, as well as a similar postcursor (a lagging event). If a minimum-phase response is required at all the processing steps, the presence of a precursor is not desirable. If the reference channel is determined by using reference traces which are nearer the source with respect to the primary channel, or by using sections of reference traces that are causal with respect to the output point, then only a postcursor will be present in the filtered data.

Method 3 Single reference channel based on median stack

The median filtering of a sequence of numbers is performed by passing a rectangular window over the sequence and replacing each point in the sequence with the median value of the points within the window centered on the current point. This 1-D median filtering operation can be applied on a 2-D data set in a specified direction to obtain an estimate of wave components incident in that direction.

The reference channel can be generated by adding the ground roll along the dominant moveout using a median stack operation as shown in Figure 6. The stacking operation is carried out locally on typically 3 to 5 neighbouring traces. As shown in Figure 6, the sensing means, or geophones, 72, 74, 76 produce reference traces 78 and 80 and a primary trace 82. The traces are used in a median stack operation. Unlike the mean, or conventional stacking operation, the median operation does not smear the seismic reflections (which do not share the same moveout as the ground roll), but suppresses them. Thus, the reference channel 90 produced by the median stack operation contains a better estimate of the interfering ground roll with less contamination by the seismic signal of interest than is possible using conventional mean stacking. This method may be performed on overlapping windows to readjust the stacking moveout.

Method 4 <u>Multiple reference channels based on median stack and moveout differentiation</u>

The previous embodiment is further developed by firstly applying median stack 114 and thereafter time shifts τ_1, τ_2 to generate the reference channels x_1 (t), x_2 (t). Figure 7 demonstrates how five traces 91, 92, 93, 94, 96 can thus be used to generate two reference channels. Signal energy as leaking through the median filter is further suppresed. This embodiment is especially useful when filtering a small number of traces or data from a small number of geophones or hydrophones.

Method 5 <u>Single reference channel based on polarisation differentiation</u>

Ground roll and seismic reflections are often polarised differently, with seismic reflections being linearly polarised and ground roll often appearing to be elliptically polarised. Polarisation filtering is used to distinguish seismic events by the inherent polarisation when the seismic wavefield is measured by multicomponent sensing means, or geophones.

A method for obtaining a reference channel from polarisation filtering of the components produced from a multicomponent sensing means is shown in Figure 8. A multicomponent sensing means 116 detects three orthogonal components u_x 118, u_y 120, u_z 122 of the reflected wave. The polarisation filter 124 filters the elliptically polarised ground roll signal

and the filtered signal is used as the noise reference 126 in adaptive interference cancelling. The original unfiltered trace 128 is used as the primary channel. Application of the adaptive filter reduces the residual energy and thus improves ground roll attenuation. This method uses data from a single three component (3C) geophone and may be applied to each individual component to recover ground roll attenuation multicomponent data.

Method 6 <u>Multiple reference channels based on polarisation and moveout differentiation</u>

As shown in Figure 9, this method uses reference geophones 130, 132 of at least 3C and a primary geophone 134. The primary geophone produces a primary channel 136, defined as at time t_0. Polarisation filters 138 and 140 are used as in Method 4 to filter the elliptically polarised ground roll signal and produce reference traces 142, 144. The reference traces 142, 144 are delayed by t_1 and t_2 so as to sample the reference traces in accordance with the moveout differentiation method as described in Method 1. The delayed reference traces are then used to provide the reference channel. It is possible to perform this method using two reference geophones, the primary channel being obtained from one of the components before filtering.

In this method of obtaining a reference channel, the two completely independent criteria of moveout and polarisation are used simultaneously to differentiate between the seismic signal and the ground roll. This method produces a more robust attenuation of ground roll than Method 4.

Method 7 <u>Multiple reference channels generated using iterated adaptive interference cancelling</u>

As discussed above, the concept of adaptive interference cancelling relies on the absence of signal components in the noise reference channels. In reality, this is rarely the case, there is almost always some signal leakage. The noise estimate from an initial run of adaptive interference cancelling may be used as noise reference in a second run, which improves the signal and noise separation obtained from the original data. Use of an iterative approach, using the filtered output signal to successively refine the output signal, may be used as many

times as is deemed advantageous. For methods with multiple reference channels, this method also has the effect of increasing the effective array aperture with only linear increase in computational complexity.

The implementation of a method in accordance with the invention will now be described for three dimensional surface surveys, i.e. land based surveys.

Implementation for 3-D surveys

In 3-D surface seismic surveys, the current practice is to deploy 2-D aerial arrays of geophones and collect data for varying azimuthal distributions of source locations. These arrays typically contain of the order of 24 geophones, and the output signal is obtained by hardwiring the geophones and summing their outputs.

Adaptive interference cancelling as described in this work may be used in 3-D surveys, with an aerial pattern of geophones, or net, for example a hexagon layout of geophones with a central geophone. If the direction of incidence of the direct ground roll (or, equivalently, the source location) is not supplied at the time of processing, this may be estimated by cross-correlating an arbitrary reference trace with the other traces. Each trace (geophone output) is in turn selected as the primary channel, and a number of corresponding reference traces are chosen so that sufficient ground roll moveout exists between the primary and the reference traces. All the filtered traces obtained by using the method according to the invention are stacked either as in conventional beamforming (mean operation), or using median stacking. The delay of each filtered trace by different τ_1 and τ_2 values ensures that the precursor and postcursor features of the signal are in general de-emphasised, while the seismic reflection is emphasised.

The areal dimensions of these geophones nets are much smaller than the hardwired aerial arrays used at present. In addition the subsequent stacking of the filtered traces preserves more of the signal bandwidth than the current practice, particularly for large source to receiver offset.

Implementation using perfect reconstruction filter banks

In most seismic surveys, the coherent noise occupies only a fraction of the temporal bandwidth available. For example, in the test data used in this work, the Nyquist frequency is 250 Hz, while most of the ground roll energy is under 30 Hz. Concentrating filtering efforts to the frequency band where the coherent noise resides is desirable to reduce computational cost. One means of achieving this aim involves adding QMF (quadrature mirror filter) perfect reconstruction filter banks to the noise suppression system using adaptive multichannel filter banks. Thus two filter banks are effectively involved in the system. The QMF filter bank is used to decompose the traces into frequency bands and decimate before adaptive filtering is applied, and then used for resynthesising. Using the QMF filter banks to decimate reduces the number of points to be processed and also allows reduction in the number of coefficients in the adaptive filters, bringing in significant savings in computer processing time and computer memory requirements.

Due to the frequency overlap needed in the design of QMF filter banks, there is some leakage between bands. The effect of this leakage can be addressed by widening the band that is processed. Additional suppression of residual ground roll can be achieved by forming conventional groups which can be seen as simple *k*-domain filters or beamformers. The methods in accordance with the invention avoid data processing problems where aliased noise such as ground roll is present.

Aliased ground roll when the geophone (or source) sampling distance is greater than that required by the Nyquist theorem. In some acquisition geometries this may be done by design to reduce the number of geophones (and/or sources) deployed in the field.

Methods which require proper sampling, like *k* or *f-k* domain filters are not able to separate the signal and the ground roll effectively as frequency domain (*k* or *f-k*) filters seek to separate the seismic signal and the ground roll in one step by assigning distinct regions in the transform domain to the signal and to the noise. The presence of aliasing prevents this. The method according to the invention does not transform the data, so it is not affected by aliasing. It focuses on the noise and removes it; the remaining data is the filtered signal.

The application of the method in accordance with the invention to processing of a real data set when compared with processing by conventional methods is now discussed. The data set used was obtained from a common receiver gather, where the spacing between Vibroseis shot point locations was 4 metres. In order to be able to inspect the effect of processing on both the signal and the noise before stack, two synthetic reflections were added. Further evaluation of the processing was performed after adding arbitrarily spike-type noise to the data set.

Performance of the conventional grouping techniques was simulated by arithmetic averaging of adjacent traces in moving windows. With a conventional group of 6 (20 metre group), some ground roll suppression could be achieved, but the distortion of the seismic event has increased.

Where the data was analysed using a known normalised LMS algorithm in the adaptive interference cancellation, the normalised LMS algorithm failed to track the ground roll. The method of adaptive interference cancelling using the LMS algorithm has limited success in suppressing the ground roll. The LMS algorithm does not converge fast enough to cope with the transient and non-stationary nature of the ground roll.

On applying the method according to the present invention to the test data set, the use of the multichannel filter bank preserves the seismic reflections well, and the ground roll is effectively suppressed. In this example N=2, ie there were two reference channels for each primary channel, and L=30, ie there were 30 coefficients for each channel. The output windows $h_i(t)$ were triangular with length 100. $\Delta\tau_1 = \Delta\tau_2 = 3$ samples. p=5 was the number of principal components used.

The method in accordance with the invention may be used with incoherent noise sources other than ground roll, such as steamer noise and rig noise in marine surveys, or sea bottom surveys.

In marine seismic surveys, an acoustic source generates waves which travel through the water and into the earth. These are then reflected or refracted by the sub-surface geological formations, travel back through the water and are recorded by long hydrophone arrays which are towed near the surface of the water behind a seismic vessel. The hydrophones are mounted in streamer cables, or streamers. There are usually 2-12 streamers towed which are each several kilometres long. The streamers are made up of 100 metre long sections; each section consists of hydrophones inside an oil-filled skin. Stress-wires and spacers form the internal skeleton of the streamer.

While the streamers are being towed behind the vessel, self-noise is generated due to a variety of sources. The lurching of the vessel, especially in rough seas, causes vibrations in the stress-wires which interact with the connectors and the oil-filled skin, generating bulge waves (or breathing waves) which propagate down the streamers. The pressure variations are detected by the hydrophones, adding and corrupting the detected seismic signals. As the streamer moves through the water, boundary layer turbulence causes pressure fluctuations at the outer skin wall, which are again coupled to the hydrophones.

The adaptive interference cancelling methods according to the invention are directly applicable to the bulge wave. Previous uses of adaptive interference cancelling in relation to make seismic surveys have had to utilize special sensors (stress sensors or accelerometers) to form noise reference channels, see US 4821241, US 5251183. The methods according to the invention form noise reference channels using only the hydrophone data. The methods using 3 component data and polarisation filtering are not applicable to the streamer noise problem, but the other methods are applicable.

In some marine seismic surveys, there is interference which is incident in the cross-line direction to the streamers. One such case is the presence of interference coming from drilling activity on an oil rig. Since there may be as few as two streamers being towed behind the vessel, an array of hydrophones formed in the direction of the interference would not have sufficient number of hydrophones to utilise conventional beamforming, or data-independent multichannel filtering, such as *f-k* filtering. On the other hand, the adaptive interference cancelling methods according to the invention are directly applicable

to this problem. Along the cross-line array,, the interference will have greater moveout, or apparent slowness than the seismic signals, and this feature is exploited in applying the adaptive interference cancelling methods.

The use of the methods according to the present invention permits a large reduction in the numbers of geophones or hydrophones required to acquire seismic data.

Claims

1. Method for filtering noise from discrete noisy seismic signals in a time interval ([1, ..., T]), said method comprising the steps of

- using said noisy seismic signals for determining at least one reference channel (**x(t)**) for said time interval as an estimate of said noise;
- determining coefficients for M temporally local filters (**w(i,t)**), said filters forming a dilter bank, and M being a number equal to or larger than two, by minimizing a cost function (**J(t)**) representing a measure of the error of the output of said filter bank; and
- applying said filter bank to said at least one estimate (**x(t)**) to determine M filtered estimates of said noise.

2. A method according to claim 1, wherein the cost function (**J(t)**) is temporally global, representing a measure of the error of the total output of said filter bank in the time interval([1, ..., T]).

3. A method according to claim 1, including the step of multiplying M filtered estimates with temporal window functions ((**h(i,t)**).

4. A method according to claim 3, wherein the temporal window functions are characterized by the requirement that only adjoining windows overlap.

5. The method of claim 3, wherein the cost function (**J(t)**) is minimized using the approximation that the sum, weighted by window functions, of the output of adjacent filters of the M filters (**w(i,t)**) is equal when applied to the same signal in time regions where said window functions overlap.

6. A method according to any of claims 1 to 5, wherein global optimisation of the filtered output signal is solved by the method of principal components.

7. A method according to any of claims 1 to 4, wherein the global optimisation of the filtered output signal is solved by a damped least squares approach.

8. A method according to claim 6, wherein the number of principal components is adjusted to vary the degree of filtering.

9. A method according to any of the preceding claims, wherein adaptive filtering is achieved by use of a filtering means, comprising a plurality of local filters.

10. A method according to claim 9, wherein each local filter is a multichannel filter.

11. A method according to any of claims, wherein the filtered output signal is reprocessed in an iterative manner to further filter the noise.

12. A method according to any of the preceding claims, wherein the reference signal is obtained by moveout differentiation of data signals.

13. A method according to any of claims 1 to 11, wherein the reference signal is obtained by median stacking.

14. A method according to claim 13, wherein the median stacking is followed by moveout differentiation of the stacked signals.

15. A method according to any of claims 1 to 11, wherein the seismic data is obtained from multicomponent sensing means, and the reference signal is obtained by polarisation filtering of each component sensed by the sensing means.

16. A method according to claim 15, wherein polarisation filtering is combined with moveout differentiation.

17. A method for filtering noise from seismic data signals, substantially as herein described with reference to and as illustrated in the accompanying drawings.

18. Use of the method of claim 1 in a seismic 2D or 3D survey of land, marine, or transitional zone.

Application No: GB 9600341.3
Claims searched: 1-18

Examiner: David Summerhayes
Date of search: 25 April 1996

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1G (GEL, GER, GMB, GMC)

Int Cl (Ed.6): G01V (1/36)

Other: ONLINE: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
	None	

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